Innovative Quantum Technologies for Microgravity Fundamental Physics and Biological Research

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Abstract—The many advanced technology requirements dictated by the demanding low-Earth orbit research environment can only be satisfied through the adaptation of innovative methods and technologies. The fundamental physics research program currently supports research in four areas: gravitational and relativistic physics, laser cooling and atomic physics, low temperature and condensed matter physics, and biological physics. The microgravity fundamental physics is one of the science disciplines within the new NASA Office of Biological and Physical Sciences Research, where quantum technology plays a major role. Quantum technology, based on controlled manipulation of fundamentally quantum processes of atoms, molecules, or soft matter, enables novel and significantly extended capabilities. This paper presents a new technology program, within the fundamental physics, focusing on four quantum technology areas: quantum atomics, quantum optics, space superconductivity and quantum sensor technology, and quantum fluid based sensor and modeling technology.

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INTRODUCTION

In the context of scientific research in microgravity, technology assumes a dual role. It enables experimental investigations by providing the means to carry out detailed and accurate measurements in a difficult environment, but it can also generate new approaches for technological advances specifically directed towards low- and reduced-gravity applications[1]. The many-advanced technology requirements dictated by the demanding low-Earth orbit research environment can only be satisfied through the adaptation of innovative methods and technologies. The fundamental physics research program in microgravity sponsors research that explores the physics governing matter, space, and time and that seeks to discover and understand the organizing principles of nature, including the emergence of complex structures. Pursuit of this research will not only expand understanding of our world and the universe, but will also lay the foundation for scientific breakthroughs of the future. In addition, as experiment instrumentation is developed that allows more sophisticated study of fundamental principles, these technologies are often transferred to use in other applications such as those related to medicine or biological capabilities. Research in this field conducted in microgravity allows scientists to test many basic principles of fundamental physics that have been either difficult or impossible to test accurately on Earth. For some types of experiments, longer observation periods are possible in microgravity; for others, the space environment provides isolation from disturbances, such as vibrations, or provides improved sample uniformity. The fundamental physics research program currently supports research in four areas: gravitational and relativistic physics, laser cooling and atomic physics, low temperature and condensed matter physics, and biological physics. The microgravity fundamental physics is one of the science disciplines within the new NASA Office of Biological and Physical Sciences Research, where quantum technology plays a major role. Quantum technology, based on controlled manipulation of fundamentally quantum processes of atoms, molecules, or soft matter, enables novel and significantly extended capabilities. This technology exploits quantum coherence, quantum interference, quantum entanglement and quantum nonlocality to achieve the aim of greatly improved capabilities.

A ten-year effort to survey the field of physics and to identify directions and priorities for the new decade has culminated in a recent report by the National Research Council's (NRC) Physics Survey Overview Committee. The committee produced a number of sub-discipline-specific volumes during its survey, and these then served as the foundation for the recent 182-page report, "Physics in a New Era: An Overview[2]." To this end, the committee identified six areas of priority for research; one of the six priority areas is developing the quantum technologies. The report says "The ability to manipulate individual atoms and molecules will lead to new quantum technologies with applications ranging

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from the development of new materials to the analysis of the human genome. This ability allows the direct engineering of quantum probabilities.... A new generation of technology will be developed with construction and operation entirely at the quantum level. Measurement instruments of extraordinary sensitivity, quantum computation, quantum cryptography, and quantum-controlled chemistry are likely possibilities."

TECHNOLOGY PROGRAM

The main motivation for initiating the quantum technology theme within the microgravity fundamental physics technology program is to create a breakthrough approach to develop sensors with significantly higher resolution and sensitivity than conventional technology. These sensors will be miniaturized, to be suitable for future micro-spacecraft, with capability to support NASA's robotic and manned flight missions, and will significantly increase science return. Although there is a lot of research under way in almost all aspects of quantum technology at Caltech and JPL, the Microgravity Fundamental Physics Technology Program will initially focus on four areas: quantum atomics, quantum optics, space superconductivity and quantum sensor technology, and quantum fluid based sensor and modeling technology.

Quantum Atomics

In the early 20th century, a technology that became known as "electronics" began a revolution that touched nearly every aspect of our lives. In the second half of the century technological advances led to "photonics" where by utilizing a photon to perform the same function as the electron does in conventional electronics, new and superior capabilities were achieved. We now stand on the threshold of the technology of "atomics" where coherent matter waves can be exploited to realize never before possible capabilities. This technology is currently the basis for novel and ultra-sensitive inertial sensors. Matter waves can be utilized to perform interferometry, a practice that leads to the most precise realization of metrology. Unlike electromagnetic waves, matter waves strongly interact with gravity, they can be the basis for extremely sensitive sensors of the inertial forces. As an example, a ring gyroscope based on matter waves of cesium atoms will have about 10^{11} times more sensitivity than a laser light gyroscope with an equivalent similar area. This factor represents the ration of the rest energy of the atom to that of the photon. Similarly, extremely sensitive gravity gradiometers based on atomics promise unprecedented capability for realizing a sensor to test the fundamental laws of physics, as well as allow sub-surface mapping of the earth and planetary structures and resources. This instrument will exhibit its largest sensitivity in the microgravity environment where the absence of gravity permits the realization of the equivalence of longer-arm interferometers. Finally, the coherent matter waves of Bose-Einstein Condensation, atom lasers, promise to find as many diverse applications as the conventional light laser that is ubiquitous in today's advanced technology society. These are but a small sample of new capabilities that the sub-field of quantum atomics can provide for improved sensors for earth and space.

Quantum Optics

Quantum optics, a field concerned with the coherence properties of light and its influence on interaction of light with matter, is yet another sub-field of quantum technologies. It has already led to advances in a number of research fields, such as coherent spectroscopy. Yet many vistas of this rich field remain undiscovered or unexplored for technological applications. Recent advances in this field have led to creation of slow light in atomic vapors, as well as light traveling faster than its vacuum speed in atomic vapors specially prepared by laser irradiation. These observations are poised to create new applications that can influence diverse fields, such as realization of phase array antennas requiring precise true time delays, and controlled memories with large storage capacity. Beyond this, the realization of a single photon, on demand, laser is poised to significantly improve our capability in communications by allowing the implementation of quantum algorithms that allow communication over noisy channels, as well as creation of orders of magnitude improved data rates based on super dense coding. A major promise of quantum optics is creation of new sensors for biological and pre-biotic molecular research. These sensors may enable the study of biological entities at single molecular level to provide the needed understanding to link biology with the underlying laws of physics. They also lead to the needed capability to detect life beyond earth, as well as the presence of harmful molecules in space habitats. Quantum optics will thus create technologies that vastly improve our lives on earth, and our capabilities to explore space.

Space Superconductivity and Quantum Sensor Technology

The modern technology based upon superconductivity not only enabled many new sciences but also improved our daily life, for instance, a super-conducting magnet used in Magnetic Resonance Imaging (MRI) and a super-conducting wireless filtering system for cellular phone networks. The Super-Conducting Quantum Interference Device (SQUID) sensor based on super-conducting technology provided opportunities to discover many new physical phenomena during the last few decades, and its technology has been significantly improved as other supporting technology enhanced. This sub-theme, "space superconductivity and quantum sensor technology" was selected based upon JPL's unique experience and core competency in this area. As an example, the cold accelerometer and SQUID array sensor development will directly impact quality of the current and future science on the International Space Station (ISS) supported by NASA. Other technology areas are magnetic imaging and inertia measurement technology. These technologies will impact other science disciplines.

Quantum Fluid Based Sensors and Modeling Technology

Since the first time helium was liquefied at a temperature of 4.2 K, liquid helium has been one of the most intensively studied materials because it possesses exotic and unique properties. Many Nobel prizes in physics were awarded to discoveries associated with the quantum nature of ^{3}He and ^{4}He at low temperatures. In the modern era, scientists are re-evaluating the quantum properties of the super fluid ^{3}He and ^{4}He with fascinating applications in mind, for instance, a gyroscope, particle detectors, etc. The sub-theme called "quantum fluid based sensor and modeling technology" is chosen to develop these unique applications. JPL has many experts in this field. For instance, the Josephson effect in super fluid ^{4}He has been recently observed by JPL scientists[3]. Potential benefits of this sub-area are broader in the sense that it will impact other science possibly beyond microgravity research science, for instance, earth science and astrophysics.

NATIONAL AND INTERNATIONAL COOPERATION

The Fundamental Physics Technology Program at JPL places much emphasis on cooperating with other Federal agencies and sharing resources in the areas of science, engineering, and technology development. We already have been collaborating successfully in advanced technology development areas with the National Institutes of Health (NIH), the National Institute of Standards and Technology (NIST), Sandia National Laboratory, with industry including Boeing, and academia including California Institute of Technology (Caltech) and Stanford University. This trend is expected to broaden in the near future to include collaboration with a larger number of Federal agencies, industry, universities, and international partners. Caltech has recently established the Institute for Quantum Information (IQI), supported by a five-year grant from the National Science Foundation. The goal of the IQI is to advance the foundations of quantum information science (QIS), an emerging field that draws on physics, mathematics, computer science, and engineering. Broadly speaking, QIS addresses how the principles of quantum physics can be harnessed to improve the acquisition, transmission, and processing of information. Central to the IQI's scientific and technological program is a vigorous visitor's program that brings to Caltech the world leaders of the QIS research community for both long-term and short-term visits. The IQI also supports postdoctoral scholars drawn from backgrounds spanning the disciplines relating to QIS. Caltech and JPL are planning to hold seminars, symposia, workshops and conferences to establish a forum for QIS research and technology and to promote collaborations in these areas. Our efforts will also include the identification of the research and technology developments for which these collaborations would be the most effective.

The First International Symposium on Microgravity Research and Applications in Physical Sciences and Biotechnology was held September 9–15. 2000 in Sorrento, Italy. The meeting built on a successful series of symposia sponsored by the European Space Agency (ESA) in light of the international cooperation that has resulted in the assembly of the ISS. At this gathering, scientists from various nations presented recent results of theoretical, numerical, and experimental investigations in physical sciences and biotechnology, and their relevance to applications-oriented research, preparing the way for the release of a Microgravity Research International Announcement of Opportunity, which the International Microgravity Strategic Planning Group issued in October 2000. The conference allowed researchers to obtain detailed information on the objectives and the opportunities of the announcement, and gave them the opportunity to discuss joint research programs with their colleagues. To further assist in this endeavor, poster sessions dedicated to the experiment hardware provided by the international partners for the ISS were also presented[4] A proposal to form an International Technology Working Group (ITWG)[5] to begin international collaboration activities has been met with great enthusiasm by the Symposium organizers and participants. We are planning to formally establish such a group, initially within the microgravity fundamental physics technology areas. We propose that members of the ITWG will:

(1) Participate in the Fundamental Physics Advisory Group (FPAG), International Microgravity Strategic Planning Group and topical group meetings, international science symposia, workshops, and conferences in order to understand, communicate and address new technology requirements.

(2) Create and maintain a web-page, available to the international microgravity research community, containing an inventory of all existing and being developed technologies as well as information on all other technology related activities.

(3) Organize technology sessions during FPAG meetings to capture technology requirements, establish priorities, and convey to FPAG the existing technology capabilities.

(4) Initiate development of the Fundamental Physics technology Roadmap.

(5) Plan and coordinate individual collaborative efforts in technology development addressing top priority requirements also with regard to their return potential to the economy.

In the longer term, we know that our civilization will need to find ingenious ways of using the resources of space and to expand into space. The continuing exploration and utilization of space will require new tools. It is the prime responsibility of the ITWG to ensure that these new tools will be always available to our international research community.

CONCLUSIONS

We are in the midst of an exciting revolution in the ability to observe and manipulate material at the quantum level. Physics and technology for next hundred years will be dominated by the technological advances associated with this new revolution. The next few decades are certain to lead to new insights into the world of quantum physics and to dramatic advances in technology. By discussing examples of innovative quantum technologies, we have shown that quantum technology is an integral and very important part of the microgravity fundamental physics research. At JPL, we will work to develop future space quantum sensors which will evolve to be more complete by sensing physical parameters, processing data, making decisions, being self replicating, propagating themselves, and forming quantum networks. These sensors will help man explore space beyond the solar system. They will also be man's robotic extensions to propagate space.

We are looking forward to working together with our national and international partners to achieve these goals. We conclude that the national and international collaborations in both fundamental physics research and technology will not only leverage all resources and eliminate duplication of effort, but, most importantly, it will also speed up future breakthroughs, specifically, in the exciting areas of quantum physics and quantum technologies.

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